Chapter 6
Vertical Control Survey Techniques

6-1. General

This chapter outlines procedures to follow when performing conventional vertical control survey work. The material presented is not meant to be rigid methodology that cannot be tailored for a particular application. The mandatory part is the classifications, standards, style of keeping notes, and general procedures required to successfully complete the particular survey. Refer to EM 1110-1-1003 for GPS survey techniques for vertical control purposes as well as any of the applicable references listed in Appendix A for further guidance on information not covered in this chapter.

6-2. Vertical Control Surveys

a. The purpose of vertical control survey operations is to establish points at convenient intervals over the area to be surveyed. These established points can then serve as points of departure and closure for leveling operations and as reference marks during subsequent construction work. The NGS, National Ocean Service (NOS), United States Geological Survey (USGS), other Federal agencies, and many FOA have established control nets throughout the CONUS. Unless otherwise directed, these benchmarks will be used as a basis for all vertical control surveys. Usually NGS level circuits are found along main highways or railroads, while most FOA-maintained control is limited to project or survey areas. Exact locations of benchmark data and their values can be found in publications issued by the agency maintaining the circuit. Information on USACE-maintained points can be found at the District or Division level offices, but are generally maintained on the NGVD 29 or NAVD 88 datum. Level circuits maintained by other agencies are not necessarily on the same datum. Therefore, the surveyor must investigate what datum is being used in a particular level circuit before crossing into it. This will minimize the possibility of errors in subsequent calculations and operations.

b. Vertical control surveys can be done at First-, Second-, Third-, or Fourth-Order, although most applications can be satisfied with Third- or Fourth-Order vertical level work. Although there are various forms of vertical control surveys, all have similar methods of operation. The main differences between them are: the accuracy with which they are run, the slightly different style of field notes required, and the equipment used.

6-3. Direct Leveling

Direct leveling is usually referred to as differential leveling or spirit leveling. The actual differences in elevation are measured. In this method, a horizontal line of sight is established by using a sensitive level bubble in a level vial. The instrument is leveled and the line of sight of the instrument describes a horizontal plane. The difference in elevation between a known elevation and the height of instrument (HI) is determined. Next, the difference in elevation from the HI to an unknown point is derived by measuring the vertical distance with a precise or semiprecise level and leveling rods.

6-4. Indirect Leveling

Indirect leveling is a subdivision of leveling which does not measure the difference in elevation between points; instead other methods are used to determine elevation differences. There are two common methods of doing indirect leveling: trigonometric and barometric.

a. Trigonometric. This method applies the fundamentals of trigonometry to determine the differences in elevation by observing a horizontal distance and vertical angles above or below a horizontal plane to compute the vertical distance between points. Trigonometric leveling is generally used for Second-Order or lower order accuracies. Trigonometric leveling is especially effective in establishing control for profile lines, for strip photography, and in areas where the landscape is steep.

(1) In typical trigonometric leveling operations, it is only necessary to measure the HI, determine slope distance, read the vertical angle, and observe rod intercept. From these data, the vertical difference in elevation can be computed using the sine of the vertical angle and applying the rod difference as shown in Figure 6-1.

(2) Refinements to this technique that can reduce the chance for errors include doubling vertical angles, taking differences both ahead and back, and using mean values.

(3) If the horizontal distance is known between the instrument and the rod, it is not necessary to determine the slope distance. This is the case because the tangent of the vertical angle times the horizontal distance will give you the same answer as the sine of the angle times the slope distance.

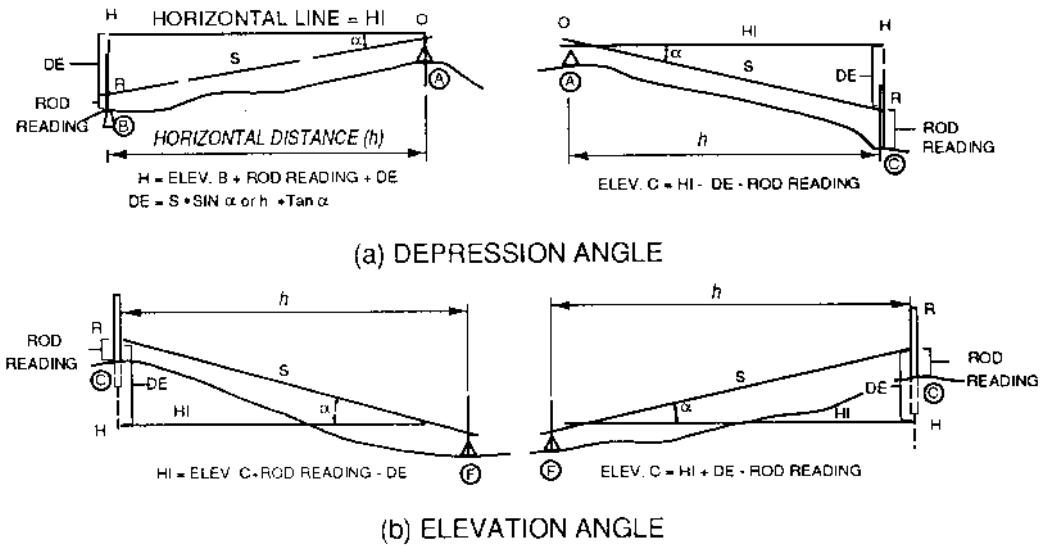

Figure 6-1. Trigonometric (or indirect) leveling

(4) Equipment. There are many types of instruments that may be used such as theodolites, transits, or alidades. The instrument used will depend upon the accuracy requirements.

(a) Theodolite. The instrument most commonly used is the 1-second directional theodolite.

(b) Transit. The transit is very seldom used by topographic surveyors today. The construction surveyor, however, will frequently be called on to use it. The procedure is the same as that of the theodolite.

(c) Alidade. With normal operating care, a telescopic alidade equipped with a Beaman arc can be used for lower order control leveling.

(d) Total station. An electronic-based instrument with features comparable to or better than those of a theodolite can be used. Manufacturers' procedures should be followed to achieve the point closure standards shown in Table 3-2.

(e) Digital levels. Digital (or Bar-Code) levels are used for fully automatic leveling. These instruments automatically measure, store, and compute heights and are capable of achieving Second-Order or higher accuracies. Manufacturers' procedures should be followed to achieve the point closure standards shown in Table 3-2.

(f) Semiprecise rods. When leveling in remote areas where the density of basic vertical control is scarce the semiprecise rod is generally used. The semiprecise rod should be graduated on the face to centimeters and on the back to half-foot intervals.

(g) Standard rods. When leveling in urban areas or areas with a high density of vertical control where ties to higher order control are readily available, the standard leveling rods are used. The Philadelphia rod graduated to hundredths of a foot can be used. Other rods that are graduated to centimeters can be used. Both types of rods are furnished with targets and verniers which will permit reading of the scale to millimeters or thousandths of a foot if required by specifications. This is generally not required on lower order trigonometric level lines.

(h) Stadia rods. The standard stadia rods can also be used for lower order level lines. The stadia rod is graduated to the nearest 0.05 of a foot or 2 centimeters. These rods are generally equipped with targets or verniers, but if project specifications require, they can be estimated to hundredths of a foot.

b. Barometric. This method uses the differences in atmospheric pressure as observed with a barometer or altimeter to determine the differences in elevation between points. This is the least used method in surveying and the least accurate method of determining elevations. This method should only be used when one of the other methods is unfeasible or would involve great expense. Generally, this method is used for elevations when the map scale is to be 1:250,000 or smaller.

6-5. Reciprocal Leveling

Reciprocal leveling is a method of carrying a level circuit across an area over which it is impossible to run regular differential levels with balanced sights (Figure 6-2). Most level operations require a sight 300 or 400 feet long, and it's often possible in such operations to set backsights a similar distance away. Sometimes though it may be necessary to shoot 500 feet, 1,000 feet, or even further in order to span across a river, canyon, or other obstacle. Where such spans must be leveled across, reciprocal leveling is appropriate.

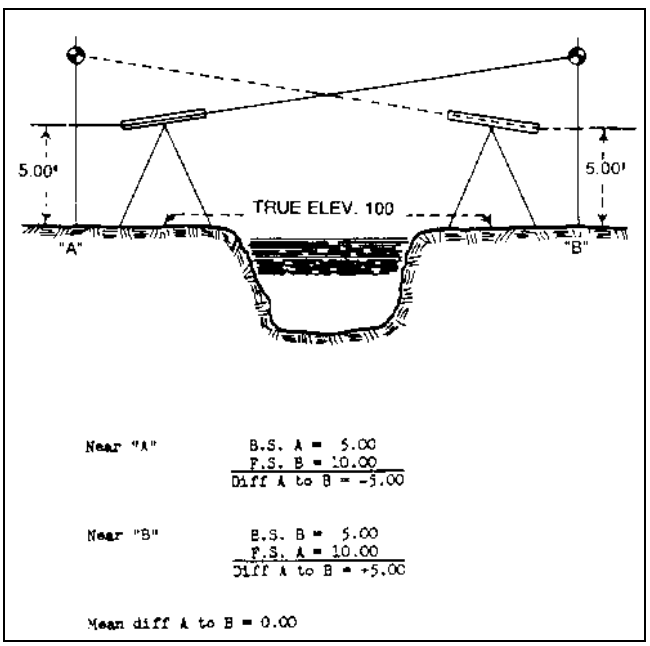

Figure 6-2. Reciprocal leveling

a. Procedure. Assume point "A" and "B" are turns on opposite sides of the obstacle to be spanned (Figure 6-2). Points A and B are assumed to be able to be sighted from an instrument set up opposite to it. Two rods should be used, one at point A and the other at point B. The rods should be first compared on a common turn to be sure they will read exactly the same (i.e., they are calibrated or a matched pair). With the instrument near A, read rod at A, then turn to B and have target set as close as possible and determine the difference in elevation. Leaving rods at A and B, move instrument around to point B, read B, then turn to read A and again determine the difference in elevation. Example calculations are shown in Figure 6-2. The mean of the two differences is the true difference to be applied to the elevation of A to get a true value of B. If the long sight is difficult to determine, it is suggested that several tries be made and an average determined. For more precise results, it may be necessary to take a series of foresights, depending on the length of the sight. It is typical to take as many as 20 to 30 sightings. When taking this many sightings, it is critical to recenter the level bubble (if applicable) and reset the target after each observation.

b. Cautions. Reciprocal leveling assumes the conditions during the survey do not change significantly for the two positions of the level. Two factors that typically may affect the result when the lengths of the sights are long are unequal expansion of the parts of the instrument and variations in atmospheric refraction. To minimize these effects, it is recommended observations be made on a cloudy, cool day if possible. Protecting the instrument with an umbrella and rapid careful collection of the readings also help to minimize these two factors. Reciprocal leveling with two instruments should never be done unless both instruments are used on both sides and the mean result of both sets used. The use of two instruments is advised if it is a long trip around the obstacle. Reciprocal leveling is effective only if the instruments used are of similar power and sensitivity.

6-6. Three-Wire Leveling

a. Accuracy. Three-wire leveling can be used to achieve any level of accuracy from First- to Third-Order, depending on the care in which the work is conducted. However, most applications do not require the accuracies possible with three-wire leveling and due to its labor-intensive nature, sound judgment must be exercised when deciding whether or not three-wire leveling should be used to establish vertical control for a project.

b. Methodology. Three-wire leveling can be applied whenever the reticule of the level has stadia lines and stub-stadia that are spaced so that the stadia intercept is 0.3 foot at 100 feet, rather than the more typical 1.0 foot at 100 feet. The stub-stadia lines in instruments meant for three-wire leveling are short cross lines that cannot be mistaken for the long central line used for ordinary leveling. A Zeiss Ni2 Self-Leveling level is an example of a typical instrument designed specifically for three-wire leveling. In three-wire leveling, the rod is read at each of the three lines and the average is used for the final result. Before each reading, the level bubble is centered. The half-stadia intervals are compared to check for blunders. For example, in a typical reading, the following values were taken and recorded and calculations made:

Upper Wire:	8.698	2.155 :Upper Interval
Middle Wire:	6.543	
Lower Wire:	4.392	2.151 :Lower Interval
Sum	19.633	
Average	6.544	

The final rod reading would be 6.544 feet. The upper and lower intercepts differ by only 0.004 foot -- an acceptable error for this sort of leveling and evidence that no blunder has been made. It is recommended that Yard rods specifically designed for three-wire leveling operations be used instead of Philadelphia rods which are designed for ordinary leveling.

6-7. Two-Rod Leveling

In order to increase the productivity in precise leveling operations, it is advisable to use two rods. When the observations are completed at any instrument setup, the rods and the instruments are moved forward simultaneously. Halfway between benchmarks, the rods should be interchanged to minimize the possible effects of index error. Two rods are recommended when using a self-leveling level, as this takes full advantage of the productivity possible with this type of instrument.

6-8. Tidal Benchmarks and Datums

Refer to EM 1110-2-1003 and FM 5-441 for guidance on the establishment of tidal benchmarks and datums.

6-9. Leveling Operations

a. General. The leveling operation consists of holding a rod vertically on a point of known elevation. A level reading is then made through the telescope on the rod, known as a backsight or BS, which gives the vertical distance from the ground elevation to the line of sight. By adding this backsight reading to the known elevation, the line of sight elevation, called height of instrument or HI, is determined. Another rod is placed on a point of unknown elevation, and a foresight or FS reading is taken. By subtracting the FS reading from the HI, the elevation of the new point is established. After the FS is completed, the rod remains on that point and the instrument and back rod are moved to forward positions. The instrument is set up approximately midway between the old and new rod positions. The new sighting on the back rod is a BS for a new HI and the sighting on the front rod is an FS for a new elevation. The points on which the rods are held for FSs and BSs are called turning points. Other FSs made to points not along the main line are known as sideshots. This procedure is used as many times as necessary to transfer a point of known elevation to another distant point of unknown elevation.

b. Second-Order leveling operations. Leveling of Second-Order accuracy levels is usually limited to control of a large area or on jobs where grades are critical. An example where Second-Order accuracy may be required is a canal where a concrete lining is used and the grades are exceptionally flat. Another example is a tunnel being dug underground for several miles where the ends may be miles apart by the route the control levels are to be run, but the aboveground distance between the ends is relatively short. On some jobs requiring such high levels of accuracy, it is desirable to close the loop being run back to the point of beginning because closing into another existing benchmark of equal or higher order may be impractical, especially if the check-in benchmark is in another leveling circuit from a completely different area.

c. Second-Order leveling accuracy. Second-Order leveling point closure standards for vertical control surveys are shown in Table 3-2. Second-Order leveling consists of lines run in only one direction, between benchmarks previously established by First-Order methods. If not checking into another line, the return for Second-Order Class I level work should check within the limits of 0.025 times the square root of M feet (where M is the length of the level line in miles), while for Second-Order Class II work, it should check within the limits of 0.035 times the square root of M feet.

d. Second-Order leveling equipment. The type of equipment needed is dependent on the accuracy requirements.

(1) Second-Order level. The instrument used in Second-Order leveling can be a total station, level, or equivalent that provides precise leveling and is constructed of materials having a low coefficient of thermal expansion. The instrument must employ the normal tilting device, and the design of the instrument must allow the bubble in the level vial to be observed by the instrument man without moving from his normal observing position. If the instrument is a level, it must be of the Dumpy type, incorporating a three-wire reticule, an

inverting eyepiece, and a three-screw base. Generally a graduated tilting screw micrometer is built into the instrument to allow reading to the nearest 0.001 of a unit. The sensitivity of the level vial, telescopic power, focusing distance, and size of the objective lens are factors in determining the precision of the instrument. These factors may vary individually, but when one factor is weakened, another factor must be strengthened to maintain the specified order of accuracy. Instruments are rated and tested according to their ability to maintain the specified order of accuracy. Only those rated as precise geodetic quality instruments (such as Wild N-3) may be used for Second-Order work.

(2) Second-Order rods. Precise level rods are required when running Second-Order levels. There are many precise rods, and any of them may be used as long as they are equivalent in accuracy to the rod described. The rods must be of the one piece, invar strip type, with the least graduation on the invar strip of 1 cm. The invar strip is 25 mm wide and 1 mm thick and is mounted in a shallow groove in a single piece of well-seasoned wood. The groove is slightly wider than the strip and deep enough so that the strip is free to move. The rod has a metal footpiece to which the strip is securely fastened. In order to eliminate any error due to sagging of the invar strip when the rod is held erect, it is placed under tension by a stiff spring, set into a recess in the top of the staff and bearing against a small brass angle plate attached to the top of the strip. This tension spring also allows the strip to expand or contract because of temperature changes. The front of the rod is graduated in meters, decimeters, and centimeters on the invar strip. The back of the rod must be graduated in feet and tenths of feet, or yards and tenths of yards. These rods must be standardized by the National Institute of Standards and Technology and their index and length corrections determined. The rods with similar characteristics are paired and marked. The pairings must be maintained throughout a line of levels. The invar strips should be checked periodically against a standard to determine any changes which may affect their accuracy. The precise level rod is a scientific instrument and must be treated as such, not only when in use but during storage and transporting. When in use the rods should be alternately carried by the handles and face up on the shoulder. If the rods are always carried with the face down or up, they will become slightly bowed and the reading will be too large. Therefore, the rods should be carried an equal amount of time by the handle and face up on the shoulder. When not in use they must be stored in their shipping containers to avoid damage. The footpiece should be inspected frequently to make sure it has not been bent or otherwise damaged.

(3) Instrument test and adjustments. To maintain the required accuracy, certain tests and adjustments must be made at prescribed intervals to both the levels and rods being used.

(a) Determination of stadia constant. The stadia constant factor of the instrument should be carefully determined. This stadia factor is required in the computation of the length from the stadia intervals and in computing the allowable error. This determination must be done for each level used in the field. Should new cross wires be installed in the field, a redetermination of the constant must be made before using the level in the survey. The observations and computations for this determination must be recorded as a permanent record along with the time and date and kept with the project files. The determination is made by comparing the stadia intervals observed over a known distance course. The course should be laid out on a reasonably level track, roadway, or sidewalk, and nails or other marks placed in a straight line at measured distances of 0, 25, 35, 45, 55, 65, and 75 m. The center of the instrument and the zero point of the instrument may not be the same for the instrument being used. The Wild N-3 level has an additive constant of -20 cm. When determining the stadia constant, therefore, the instrument must be plumbed 20 cm forward of the zero stake. For other instruments, the manufacturer's manual should be consulted. Read the rod at each of the six points and record the intervals. The level bubble need not be accurately centered, but should at least be free of the ends of the tube. The half-wire intervals should be computed as a check against erroneous readings. The sum of the total intervals for the six readings should be computed. The stadia constant is the sum of these measured distances (300 m) divided by the sum of the six total wire intervals. As a check against gross errors each separate observation should be computed. The average of the six separate computations serves as a numerical check on the computations. Any tendency for the six computed values to creep in one direction will be good evidence that some error in the measurement of the distance has been made from the center of the instrument to the zero point and then to the first of the six rod points.

(b) Determination of "C" factor. Each day, just before the leveling is begun or immediately after the beginning of the day's observations, and immediately following any instance when the level is subjected to unusual shock, the error of the level or C factor must be determined. This determination may be done during the regular course of leveling or over a special course; in either case the recording of the observations must be done on a separate page of the recording notes with all computations shown. If the determination is made during the first setup of the regular course of levels, the following procedure is used (Figure 6-3):

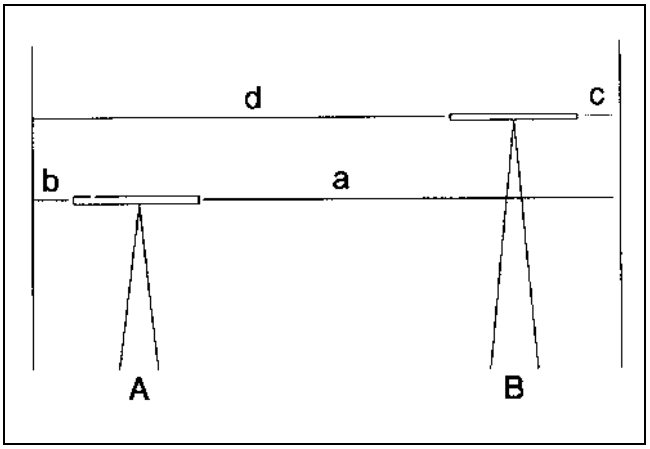

Figure 6-3. Procedure for C factor

After the regular observations at the instrument station A are completed, transcribe the last FS reading “a” as part of the error determination; call up the back rodman and have the rod placed about 10 m back from the instrument; read the rod “b,” over the instrument to a position “B” about 10 m behind the front rod; read the front rod “c” and then the back rod “d.” The two instrument stations must be between the rod points. The readings must be made with the level bubble carefully centered and then all three wires are read for each rod reading. The required C factor determined is basically the ratio of the required rod-reading correction to the corresponding subtended interval, or:

$$C = \frac{(\Sigma \text{ near rod readings}) - (\Sigma \text{ distant rod readings})}{(\Sigma \text{ distant rod readings}) - (\Sigma \text{ near rod readings})}$$

The total correction for curvature and refraction must be applied to each distant rod reading before using them in the above equation. It must be remembered that the sum of the rod intervals must be multiplied by the stadia constant in order to obtain the actual distance before correction. The maximum permissible C factor varies with the stadia constant of the instrument. The instruments must be adjusted at once if the C factor is greater than 0.004 for instruments with a stadia constant of approximately 1/100, 0.007 for stadia constants of 1/200, and 0.010 for stadia constants of 1/333. It is desirable to have the determination of the C factor made under the anticipated conditions as to length of sight, character of ground, and elevation of line of sight above the ground. The date and time must be recorded for each C factor determination, since this information is essential in computing the level corrections when making office computations for that particular day’s work.

(c) Adjustment of level. The type of instrument being used will dictate the method and procedure used to adjust the instrument, if the C factor exceeds the allowable limits. The manufacturer’s procedures should be followed when adjusting a level.

(d) Test of leveling rods. Precise level rods must be tested once each week or whenever they receive a severe shock. This test is made with the level rod bubble held at its center, and the deviation of the face and edge of the rod from the vertical are determined. If the deviation from the vertical exceeds 0.01 m on a 3-m length of rod, the rod level must be adjusted. This level is adjusted in the same manner as any other circular bubble. A statement must be inserted in the records showing the manner in which the test was made, the error that was found, if any, and whether an adjustment was made. When using other than precise leveling rods this test is not required.

e. Second-Order leveling monumentation. All benchmarks used to monument on Second-Order level lines will conform to criteria in EM 1110-1-1002. In general, all benchmarks used to monument Second-Order level lines shall be standard USACE brass caps set in concrete. The concrete should be placed in holes deep enough to avoid local disturbance, such as spading, soft-surface heaving due to winter rains, frost action, etc. If the brass cap is not attached to an iron pipe or tip, use some type of metal to reinforce the concrete prior to embedding the brass cap. Concrete should be placed in a position that is protected as much as possible. If possible, benchmarks should be set close to a fence line, yet far enough away to permit plumbing of level rod. Do not set the monument closer than 4 feet to a fence post as when the post is replaced, the benchmark usually will be disturbed. If practical, when a benchmark is monumented near a fence, paint the top 18 inches of the nearest fence post white to aid in identification of the location of the benchmark. Each brass cap must be stamped to identify it by the adopted method detailed in EM 1110-1-1002. In addition to stamping a local number or name on the cap, it is desirable to stamp true elevation on the brass cap after final adjustment has been made. The benchmarks must be set no less than 24 hours in advance of the level crew if the survey is to be done after monument construction.

f. Second-Order leveling notes. Notes for Second-Order levels will be kept in a manner approved by the immediate supervisor. A set style cannot be developed due to different types of equipment that can be employed. Elevations will not be carried in the field as they will be adjusted by the field office and closures approved prior to marking benches.

g. Third-Order or construction layout leveling. All levels run for traverse profiles, temporary benchmarks, control of cross-sections, slope stakes, soundings, topographic mapping, structure layout and miscellaneous construction layout and miscellaneous construction staking shall be Third-Order or construction levels as detailed in Table 3-2, unless otherwise directed. All levels will originate from and tie into existing control. No level line shall be stubbed off or dead ended unless by specific instructions by a designated immediate supervisor or written directive.

h. Third-Order and lower leveling accuracy. All accuracy requirements for USACE vertical control surveys will conform to the point closure standards shown in Table 3-2. The required accuracy for Third-Order levels is 0.050 M feet where M is the length of the level line in miles, while construction layout level work will conform to 0.100 times the square root of M feet. The length of the line may be determined from quad sheets or larger scale map if a direct measure between points is not available, although this is not a preferred method. Direct measure of the line is the preferred method.

i. Third-Order and lower leveling equipment. The type of equipment needed is dependent upon the accuracy requirements.

(1) Third-Order level. A semiprecise level should be used for Third-Order levels, such as the tilting Dumpy type, three-wire reticule, or equivalent.

(2) Third-Order rods. The rods should be graduated in feet, tenths, and hundredths of feet. The Philadelphia rod or its equivalent is acceptable. However, the project specifications will sometimes require that semiprecise rods be used that are graduated on the front in centimeters and on the back in half-foot intervals. The Zeiss stadia rod, fold type, or its equivalent should be used when the specifications require semiprecise rods.

(3) Lower order. The type of spirit level instrument used should be a type that ensures an accuracy in keeping with required control point accuracy. The precise type level should not be used on lower order work when other less precise instruments are available. The Fennel tilting level, Dumpy level, Wye level, or their equivalent are examples of levels that can be used. The rods should be adequate for obtaining the required accuracy. The precise invar strip rods should not be used. Any stadia rod with least readings of five-hundredths of a foot or 1 centimeter will be satisfactory. The use of turning pins and/or plates will depend upon the type of terrain. Terrain permitting, the rods may be placed on reasonably firm stones or roadways.

j. Third-Order and lower leveling monumentation. The level line shall be tied to all existing benchmarks along or adjacent to the line being run. In the event there are no existing benchmarks near the survey, new ones should be set, not more than 0.5 mile apart. Steep landscape in the area of survey may necessitate monuments be placed more often.

(1) It is desirable to set benches on permanent structures. Examples of permanent structures include head walls, bridge abutments, pipes, etc. Large spikes driven into tree roots, telephone poles at the base, and fence posts generally are acceptable for this level of work. All temporary benchmarks must have full description of what they are and where they are located. Unless they are on a turn, they may not be considered to be temporary benchmarks. No closures shown by an intermediate shot will be accepted. All temporary benchmarks must have a name or number for future identification.

(2) Turning points are a very important part of leveling. The rodman will select a suitable point or drive a turning pin in the ground until rigid with no possibility of movement. All turning points or temporary benchmarks will have a definite high point so that any person not familiar with the point will automatically hold the rod on the highest point. If solid rocks are being used for turns they must be marked with crayon or paint prior to taking reading. Be sure the rod will spin free on the high point.

(3) It is not mandatory to use targets on the rod when the reading is clearly visible. However, they are required in dense brush, when using grade rods, or when unusually long shots are necessary.

k. Third-Order and lower leveling notes. Complete notations or sketches will be made to identify shots. All

Third-Order or lower level notes will be completely reduced in the field as the levels are run, with the error of closure noted at all tie-in points. In practice, the circuit will be corrected to true at each tie-in point unless instructed to do otherwise by an immediate supervisor or written directive. Any change in rod reading shall be initialed and dated so there is no doubt as to when correction was made. Cross out erroneous shots -- never erase them. The instrument man shall take care to keep peg notes on all turns in the standard field book. The notes will be dated and noted as to what line is being run, station occupied, identification of turns, etc.

6-10. GPS Surveying

Establishing or densification of vertical control with differential carrier-phase based GPS is often difficult. GPS provides height (*h*) or height difference (*h*) in terms of height above or below the WGS 84 reference ellipsoid. These ellipsoid heights (*h*) are not equivalent to orthometric heights (elevations), which would be obtained from conventional differential leveling. Therefore, users of GPS must exercise extreme caution in applying GPS height determinations to projects which are based on conventional orthometric elevations. Using current methodology (i.e., geoid modeling and transformation software), the best accuracy achievable is Third-Order. Therefore, the use of differential carrier-phase based GPS techniques for establishing or densifying of vertical control should be limited to applications where this level of accuracy is acceptable. Refer to EM 1110-1-1003 for guidance concerning GPS vertical control surveys. Point closure standards shown in Table 3-2 should be used to classify subsequent results.